2.0 MISSION IMPLEMENTATION PLAN

This section addresses all aspects of mission implementation, and, together with material in Section 1.3.1, describes the overall mission. Observatory and operations performance requirements addressed below and shown in Table 2-1 follow the overall approach of relating requirements to the science objectives described in Section 1.3.1.

2.1 Mission Approach

The mission approach for Constellation-X uses proven technology and processes for the spacecraft (s/c), launch vehicle, and operations from start to finish. The straightforward mission design demonstrates mission feasibility and readiness to proceed to the next phase, reduces risk, and ensures that mission objectives are achieved within mission constraints. The modular approach to design allows for parallel testing and makes use of simple interfaces, reducing the cost of I&T as well as the technical risk. Observatory performance can be verified on the ground, further reducing cost and complexity. Risk areas have been identified and risk mitigation strategies developed. See Section 4.1.2.7 for a discussion of risk management.

This section describes a Reference Mission design and architecture[24] developed by GSFC and SAO and which includes study results from TRW and Ball Aerospace done under NASA Cooperative Agreement (CAN-555-46-232). This reference configuration is one viable way to meet the science requirements: it proves the mission concept, aids in costing and requirements management, and forms the basis for trade studies. Future proposals will be compared with the reference design to verify that these solutions can meet mission requirements.

2.2 Launch, Trajectory, and Orbit Characteristics

2.2.1 Launch

Two separate launches, each of two observatories, are planned. Each pair of observatories will be launched side by side within a single fairing (Foldout 2). The Atlas V launch vehicle is the baseline for the Constellation-X mission because it better suits the volume and mass characteristics of the payloads, although the Delta IV remains an option. Both launch vehicles had their successful maiden flights in 2002 with commercial payloads rather than dummy loads.

The Atlas V 551 launch vehicle has a usable diameter of approximately 5 m and length of 16 m; the payload fairing (PLF) meets the volume required by the side-by-side Constellation-X observatory configuration. The Delta IV 4450-14 launch vehicle has a medium fairing with a usable diameter of approximately 5 m and length of approximately 14 m. Use of a Delta IV requires an extendable optical bench. Either launch vehicle can insert two Constellation-X observatories weighing more than a total of 5,000 kg into the lunar phasing loop orbit.

The observatories will be launched from Cape Canaveral Air Force Station in Florida. Launches are planned for 2010 and 2011.

2.2.2 Trajectory and Orbit

The Constellation-X orbit is a thermally stable Lissajous orbit at the L2 Sun-Earth libration point, like that used on the Microwave Anisotropy Probe (MAP) mission. The L2 point is located on the Earth-Sun line on the anti-Sun side of the Earth, about 1.5 million km away. The orbit provides high viewing efficiency because targets are not eclipsed by the Earth. Each of the four observatories will move about L2 with an approximately 6-month period and a maximum distance from L2 of approximately 300,000 km.

Each pair of observatories will be launched using a single launch vehicle. After launch they will be separated into non-intersecting injection orbits to avoid collision. After separation, each observatory will be maneuvered into a series of phasing loop orbits about the Earth, perform a lunar gravity assist, then follow a cruise trajectory (approximately 100 days) to L2 to its unique orbit. See Foldout 2 for a schematic of this orbit insertion.

The total ΔV required is approximately 177 m/sec per observatory. This includes correcting for launch vehicle errors, targeting the lunar gravity assist, mid-course correction maneuvers, Lissajous orbit insertion, and station-keeping maneuvers. Routine station-keeping maneuvers will be performed approximately once every 90 days.

2.3 Operations Concept

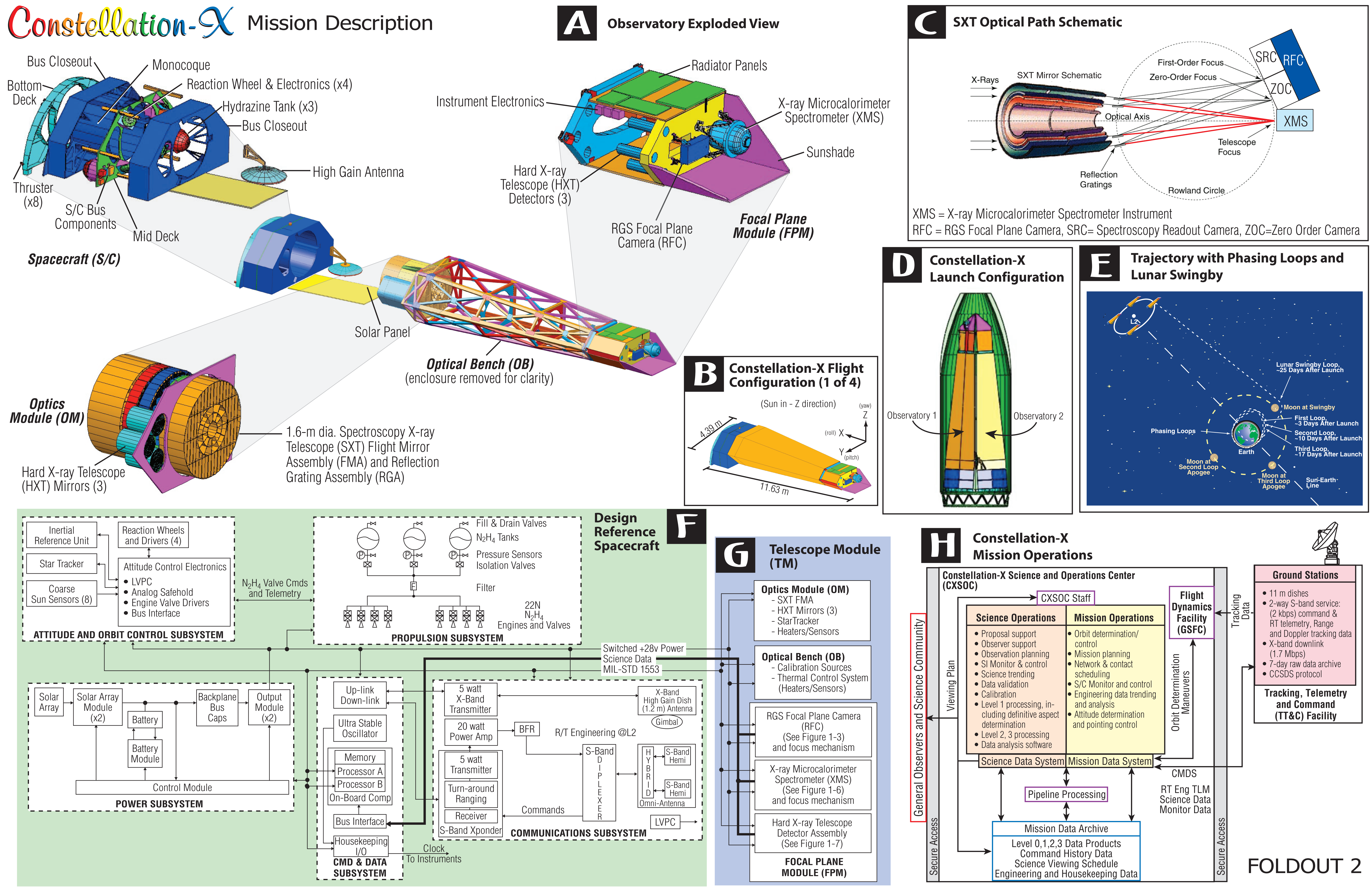
Top-level requirements that flow to the Operations Concept[25] are shown in Table 2-1.

The Constellation-X Science and Operations Center (CXSOC) will evolve from, and be co-located with, the Chandra X-ray Center (CXC) at SAO. This approach is low-risk and

Table 2-1: Driving Observatory and Operations Performance Requirements

Primary Impact On:	Parameter	Requirement	Source/Rationale	Performance
Observatory	Telescope pointing (aspect) determination ground-based post processed	5 arcsec, 3σ	Flowdown from aspect determination error budget to meet the celestial location knowledge, Table 1-1	Derived star tracker attitude knowledge requirements is 3 arcsec, 3σ
Observatory	Pointing Control	30 arcsec pitch/yaw; 60 arcsec roll	Maintain target within instrument FOV	AOCS system meets the requirement
Observatory	S/C Data Storage	On-board memory sized for 3 days normal ops plus 1 bright source observation	Flowdown from Ops Concept to allow missed contacts	43 Gbits for each observatory: sized from instrument data rates (all operate simultaneously)
Observatory	Redundancy	No single failure will result in the loss of more than 25% of the mission science	TLRD	Constellation of 4 observatories, each with redundancy in critical systems
Observatory	Reliability	Probability of mission success shall be 75% at the end of the normal operations life	TLRD	Each observatory shall be critical-component redundant
Observatory	Contamination Control	Level 100 A/3 at launch on all optical surfaces; 100 A at EOL	TLRD, Contamination Control & Implementation Plan: minimize loss of effective area and calibration uncertainties	Dry N_2 purge system (GSE) during I&T and up to launch, witness sample monitoring, adherence to MSFC 1443 for materials selection
Observatory	Mass	Meet vehicle throw weight, with margin	RMD	2476 kg observatory mass meets the requirement with 34% margin
Observatory	Power	Meet observatory power needs EOL with margin	RMD	1075 W EOL meets the requirement with 34% margin
Observatory	Propulsion	Consumables sized to achieve and maintain L2 orbit for minimum of 6 years	TLRD	Tanks sized to meet 10-year goal; wet mass sized for 6-year requirement
Observatory and Ground Segment	Telemetry Volume	Capable of downlinking 1 day of data per pass; 1 hour per pass	Flowdown from Ops Concept, in conjunction with onboard storage limit	X-band antennas and ground stations sized to meet requirements with link margin
Observatory and Ground Segment	Downlink Frequency	1 downlink/day/observatory	Ops Concept: joint requirement on sizing of on-board storage	1 downlink/day planned for each observatory
Observatory and Ground Segment	Timing	Arrival time accuracy of ±100 microseconds (UTC)	TLRD	Arrival time accuracy ±90 μsec
Observatory and Ground Segment	Mission Duration	4 years normal operations with all satellites	TLRD, Table 1-1	Systems designed to meet requirements
Observatory and Ground Segment	Observing Efficiency	90%	TLRD, Table 1-1	L2 orbit
Observatory and Ground Segment	Sky Coverage	90% 2x/year, 100% 1x/year	TLRD	Design meets requirement
Observatory and Ground Segment	Data Uplink Volume	4 Mb	Ops Concept	Design meets requirement
Observatory and Ground Segment	Data Uplink Frequency	Once/week	Ops Concept	Science Observing Plan generated and uplinked weekly
Observatory and Ground Segment	Data Latency	2 weeks (72-hour goal) from completion of observation to product delivery	TLRD	Ground system requirement meets requirement.
Ground Systems	TOO Frequency	Approx. 2x per month	TLRD, Table 1-1	Design exceeds requirement
Ground Systems	TOO Response Time	<24 hours	TLRD	Meets requirement
Ground Systems	Archive Storage	10 years of all raw and processed (to Level 3) mission data, plus reprocessing	Ops Concept, Table 1-1	Ground system design meets requirement

Constellation-X Mission Description



leverages a significant investment by NASA in facilities and expertise. Planning for transition has been initiated. No difficulties are seen in the time frame for CXSOC development. The CXSOC is the primary interface between the General Observer (GO) and the mission. The architecture of the CXSOC is described in Section 2.4.2 as is a discussion of data validation, analysis, and archiving.

CXSOC personnel consist of the following functional teams: Flight Operations, Ground Operations, Mission Data, Systems Engineering, Technical Support, and the Science Division (which works closely with the Science Instrument teams).

Because no inter-observatory communications are required, each observatory is treated separately, and constellation management issues are reduced to managing four identical but independent s/c. CXSOC software contains unique identifying tags for each observatory, ensuring proper control. This allows for re-use of the CXC mission operations tools to the greatest possible extent.

2.3.1 Operations Development

Operations development begins at the start of the implementation phase, with development of the mini versions of the CXSOC Mission Data System (MDS). These provide uniform command, telemetry, data management, and trending functions for use during development, I&T, and flight operations. This minimizes duplication of effort and maximizes commonality in procedures and databases and hence ensures continuity between development and flight operations. The Electrical Ground Support Equipment (EGSE) used by the instrument teams will be planned for integration at the CXSOC to support mission operations.

2.3.2 Launch and Early Orbit

Launch and early orbit support for each launch (two observatories) will last approximately 100 days. The two observatories will be contacted several times per day for health and safety monitoring, observatory checkout and configuration, orbit maneuvers, and science instrument turn-on and initial checkout. Instrument calibrations and checkouts will also be performed during the transit to L2. The Flight Operations Team (FOT), with support from an extended Technical Support Team (TST), will conduct Launch and Early Orbit activities. The TST is composed of civil service, observatory prime contractor, and CXSOC staff. GSFC will provide the Mission Director, and the CXSOC contractor will provide the Mission Manager. Activities associated with launch of the second pair of observatories will be kept physically separate and operationally independent from the ongoing routine operations of the first pair of observatories by using separate hardware and software.

Members of the observatory and instrument test teams will augment the normal operations team during this phase to perform checkouts and verification. After completing this activity, the extended TST will disband and the mission will transition to normal science operations. The core TST will be on-call if needed.

2.3.3 Normal Operations

A long-term Science Plan will be generated based on the accepted proposals submitted by prospective GO. This plan is a timeline of all the current cycle’s time-constrained observations. The remaining (non-constrained) targets will be allocated to one-week slots or pools based on observation length, target visibility, momentum management, and other relevant factors with the goal of maximizing the observing efficiency.

During normal science operations, the CXSOC Science Mission Planning staff will prepare weekly observatory schedules using the Science Plan for the current cycle. This plan, which will be uplinked to each observatory, is a time-ordered set of RA and Dec for specific targets and occasionally a specified roll angle about the boresite. It will include a start/end time to conduct the observation, which may range from 30 minutes to 48 hours in duration. Up to 30 observations will typically be scheduled per week; the sequence of these targets will be selected to help maximize observing efficiency and minimize the momentum buildup in the observatory, as well as meet other observatory pointing constraints. Each target will also have an associated estimated fill rate of the onboard data memory, accurate to approximately 10% after in-flight calibration. The on-board data memory has been sized to accommodate three days of normal operations at the highest nominal mode record rate, plus one day of Target of Opportunity (TOO) operations to allow for flexibility in dumping the memory.

After the observatories are maneuvered to a new target (performed simultaneously to maximize viewing efficiency), any required momentum adjustments will be performed (no more frequently than once every three weeks), and the onboard antenna will be pointed toward the Earth through a combination of antenna tilt angle adjustments and observatory roll angle selection. The FOT will integrate additional observatory activities unrelated to the science observations into the schedule. Constellation-X ground stations will be scheduled for routine operations support using a Contact Plan, which will be generated automatically by the FOT. The Contact Plan will be flexible to allow some leeway in the specific time and/or station used.

At least one (one-hour) ground contact per day to each observatory will be required. During each contact, the on-board data memory will be dumped, and any necessary commands will be uplinked. Tracking data will be collected to refine orbit knowledge. Two stations, separated by at least 40 degrees latitude, will be used on alternate days to achieve the required orbit determination (OD).

The daily downlink of science and engineering telemetry data will take place using a file transfer protocol and be captured in the Constellation-X Mission Data Archive. Nominally, there will be one science observation per file, reducing the need for Level Zero Processing (LZP). The CXSOC will convert the data into Flexible Image Transfer System (FITS) formats; initiate all pipeline processes to be used to validate, process, and calibrate the data; produce mission-related information; and distribute (push/pull) the results. Data products include instrument health and safety, trending information, and the post-facto aspect determination required to meet the celestial pointing accuracy requirement.

Approximately two TOO operations per month may be conducted, which ensures that their execution does not present an excessive burden to operations. A TOO requires that a new observation plan be generated, validated, uplinked, and executed within 24 hours. This amount of data may require additional station passes to downlink the data and will be scheduled separately from routine operations.

2.3.4 Calibration

The CXSOC, with support from the instrument teams, is responsible for planning, implementation, and analysis of the telescope and science instrument calibration of the constellation. Products derived from the analysis of the calibration data are archived to the mission Calibration Database (CalDB). The CXSOC will determine the ground and on-orbit measurements needed to accomplish these calibrations to the accuracy defined in the Calibration Plan[26] and the on-orbit viewing time required to maintain them. The CXSOC will establish calibration viewing requirements prior to each Peer Review, as well as verify that these calibration observations are properly folded into the science plan and the onboard schedule. The CXSOC is responsible for defining the CalDB implementation, its interface to the Science Processing and Analysis software, and for maintaining its content. The CXSOC is also responsible for providing the user interface to the CalDB, and supporting the GO.

2.3.5 Constellation Management

Because the observatories are essentially operated independently and are contacted sequentially only once per day, the existing software systems will be able to handle the mission with few changes. Several operations functions (e.g., station scheduling, trending generation, momentum management, antenna pointing, orbit determination, data management, attitude refinement, timing, correlation, etc.) are easily automated, and other functions produce identical results for all four spacecraft (e.g., science scheduling, attitude maneuvering, etc.). Consequently, these functions result in a small increase in the amount of work over a single observatory. For those functions that are unique to each observatory (e.g., orbit maneuvers, anomaly resolution, etc.), there is a small increase in workload over a single satellite. Flexibility in anomaly resolution is provided by the fact that an anomaly on one observatory does not affect the operations of the remaining observatories, since this is not an interferometric mission. Experience gained with the operations of the first two observatories will be applied to the operations processes of the second pair of observatories.

2.3.6 Staffing

During each launch and early orbit phases of the mission, there will be full shift coverage until stability is achieved. During the transfer orbit, which will last approximately 100 days, and during orbit maintenance activities, staffing will be commensurate with planned activities. The goal is for routine operations to be staffed during a single 8-hour shift 7 days per week. Anomaly recovery and TOOs will likely require some science and operations elements to be on call 24 hours/day, 7 days/week.

2.4 Mission Architecture

2.4.1 Flight Segment/Observatory Concept

Each observatory consists of a TM, and a s/c bus, discussed later in this section (see Foldout 2). The modular configuration of each identical observatory allows parallel processing up to final integration and streamlines I&T. The modules have simple interfaces. The s/c design is straightforward and contains hardware based on mature technologies that have flown successfully on many NASA missions.

2.4.1.1 Telescope Module

The TM comprises mirrors, science instruments, structure, and other associated equipment that combine to form a functioning telescope. This section addresses TM requirements not covered elsewhere.

The TM is subdivided into three modules:

- The Optics Module (OM) includes the SXT FMA, HXT mirrors, star tracker, associated kinematic mounts, and supporting structure.
- The Focal Plane Module (FPM) includes the XMS, the RGS FPC, the HXT detectors and associated electronics, focus mechanisms, support structure, and sunshade.
- The Optical Bench (OB) is a five-sided optical metering structure between the FPM and the OM and also includes both active and passive thermal control systems, X-ray baffles, and electrical harnesses.

TM Structure and Alignment: The TM structure maintains the SXT and HXT mirrors and their respective detectors in precise alignment to each other. The telescope has a nominal 10-m focal length (from optic node to focus). The TM structure is designed to facilitate initial alignment during assembly and maintain alignment through launch and on-orbit operations. Stiffness must be sufficient to maintain alignment in the presence of dynamic disturbance. The first resonant frequency must be greater than 15 Hz. TM components include alignment aids for optical alignment. The TM structures are made of graphite-reinforced epoxy (GREP) optimized for low CTE in specific directions. Two concepts for the OB are under consideration: a truss structure covered with multilayer insulation (MLI) for stray light closeout and a GREP shell structure.

Alignment and alignment stability tolerances between the mirrors and the detectors are given in Table 2-2 along with telescope co-alignment requirements. These tolerances are driven by effective area and angular requirements based on system error budgets as shown in Tables 1-2 and 1-3. These tolerances limit misalignment effects on image resolution to under 1 arcsec (HPD) and effects on throughput to under 1%. Alignment to these tolerances is straightforward and well understood. The alignment process will be similar to the successful process that was used to align the Chandra telescope (not the Chandra mirror).

In Table 2-2, the terms X, Y, and Z refer to displacements between the respective detector center and the mirror focus, in mirror coordinates, and to rotations of the detector axes relative to optical axes. X refers to focus errors (see Foldout 2). The tolerances were derived based on imaging error budget terms. Y and Z are lateral offsets of the detector center from focus position. The lateral stability tolerances

Table 2-2: Alignment and Co-alignment Requirements

Alignment Precision ± Stability	δX (mm) focus	δY (mm) lateral	δZ (mm) lateral	δθX (arcmin) rotation	δθY (arcmin) tip	δθZ (arcmin) tilt
RFC to SXT FMA	1.0±0.2	2.0±0.1	2.0±0.2	4.0±0.5	4.0±0.50	4.0±0.5
XMS to SXT FMA	1.0±0.2	0.7±0.1	0.7±0.1	4.0±0.5	4.0±0.50	4.0±0.5
HXT mirror to HXT detector	10.0±0.2	0.7±0.2	0.7±0.2	4.0±0.5	4.0±0.50	4.0±0.5
HXT/SXT co-alignment	N/A	N/A	N/A	N/A	>0.25	>0.25

were set to limit the image degradation contribution of SXT to detector instability during an observation, per the error budget. HXT tolerances were set in a manner similar to the SXT, with different sensitivities, particularly the effect on image resolution of focus errors. Performance is relatively insensitive to rotations of the detectors. The co-alignment tolerances are defined in terms of boresight-to-boresight rotational alignment. The primary pointing direction will be along the SXT boresight, since the XMS has the smallest detector FOV. Alignment of each HXT boresight to within 0.25 arcmin of the SXT boresight, coupled with the stated HXT lateral tolerances, provides for HXT operation no more than 0.5 arcmin off-axis. This enables HXT image resolution and throughput allocations to be met.

TM Mechanisms: The XMS and the RFC detectors each have on-orbit focus mechanisms to ensure operations at best focus. The TM also includes a combination sunshade/contamination cover in front of the SXT and a contamination cover attached to the aft end of the SXT.

The SXT forward and aft contamination covers are open-once-only mechanisms driven by springs and controlled by pin-pullers. The forward contamination cover acts as a sunshade when open. These covers protect the SXT from contamination during assembly, integration, test, and launch (the HXT has windows with vents). All of the mechanisms have Chandra heritage and have proven to be highly reliable.

Interfaces: The s/c envelops the OM. Three hard points on the s/c carry a mechanical interface with the TM structure. Instrument electrical interfaces include a multiplexed data bus, dedicated high-speed digital links, and an unregulated DC power bus. All instrument data are digitized within the instrument electronics, allowing the s/c-to-TM interface to be completely digital.

TM Thermal Control: Overall, the TM must be controlled so that the TM structure, instruments, and optics maintain required operational temperatures and alignment stability. The observatory is configured so that the detectors, which generally require a cool environment, are located at one end of the TM with a view to deep space, and the optics, requiring a room temperature environment, are enveloped within the s/c. The passive foundation of the control system uses MLI wraps and sunshades to minimize radiation loading and balances losses to cold-bias certain TM elements. Control is attained by active local heating and cooling.

OM Thermal Control—The SXT mirror must maintain absolute temperature and gradients close to the conditions under which the mirror was assembled. These requirements are mainly driven by the overall angular resolution requirement and the CTE of the materials in the mirror assembly. The thermal tolerances for the SXT are defined in Table 1-4. The thermal design will be optimized during the iterative optical-mechanical-thermal design process, accounting for all features including glass and housing.

Pre- and post-collimators as successfully used on Einstein, ROSAT, and Chandra, control heat flow through the main mirror. A collimator works by reducing view factor and thus radiation losses. It also provides a surface for thermal coatings that further reduces losses, and it provides an assembly for mounting heaters and blankets to control gradients in reflectors.

The RGA, mounted between the SXT mirror and the post-collimator, requires 1° C absolute temperature gradient control, as achieved in XMM-Newton with a similar design.

The HXT mirror assembly uses aluminized membranes covering the front and rear optical apertures. Actual thermal control is provided by heaters on the HXT structure. MLI and insulation mounts are also used to isolate the HXT from its environment.

FPM Thermal Control—FPM thermal control is achieved by MLI wrap of the electronics bay and instrument platform, a sunshade to block direct solar loading on the instruments, and available cold views of space. Some active heater control of structural elements will be used to maintain alignment stability during observations. The exterior anti-Sun surface of the bay is reserved for electronics, cryocooler and detector radiators. Apertures in the instrument platform will be minimal and designed to lessen thermal load on the instruments from the electronics bay.

XMS temperature is controlled within the XMS cryostat. However, the instrument relies on TM thermal control for its external conductive and radiation environment. FPM thermal control designs must include provisions for safe-hold conditions so that the electronics and cryocooler do not get too cold.

OB Thermal Control—The OB is wrapped in an MLI blanket. Active thermal control is provided by heaters on the OB. The interior is mostly open to accommodate the converging telescope beams, but it also facilitates a stable interior thermal environment. Adequate margin will be designed into the cold-bias to maintain control following degradation of the MLI and any radiating surfaces.

Visible Stray Light Control: Stray light over the band 300-1100 nm will be limited at the entrance aperture of the RGS CCD detector to less than 2×10^9 photons/cm^2/second. This will be achieved by careful closeout of the TM and will be tested during telescope integration by a "solar lamp test." Ascent venting of the mirror and telescope cavities will be provided for by incorporation of baffled vents. Vent paths must strictly limit the pressure differential during launch, but must be baffled to limit stray light.

Cosmic X-Ray Background Baffles: The cosmic X-ray background (non-imaged) on the XMS should be limited to 0.01 counts/sec over the SXT PSF. Protection from cosmic X-ray background is provided for each of the telescopes by a set of X-ray baffles that block the view from each detector to sky that is outside the FOV. The planar baffles are fabricated from GREP for strength and rigidity with a thin layer of tantalum applied to the detector side of the bulkhead to block X-rays and eliminate florescence from the GREP.

Calibration Sources: Calibration sources, in addition to those mounted within the detectors, are carried within the OB. They include passive radioactive sources (Fe^{55}, etc.) and (possibly) an active electron impact source. The sources will have an actively driven, fail-safe cover to allow them to be used as needed and not compromise the X-ray data.

Radiation Protection: An on-board radiation detector will be carried and used to autonomously safe the instruments in high radiation environments. A modified version of the AmpTEK™ Compact Environmental Anomaly Sensor (CEASE) has been baselined. This sensor is currently used in several Department of Defense programs to provide inputs to the radiation safing system.

2.4.1.2 Spacecraft Bus

All Constellation-X subsystems use mature technologies, proven designs, and proven s/c components that are easily obtainable from several vendors. Baselined components were used successfully on previous s/c including MAP and EO-1 and will be adapted for use on Constellation-X, resulting in a design that is essentially "off-the-shelf." The subsystems described in the following paragraphs reflect the in-house s/c design adopted for the Reference Mission, including the Atlas V, and trace back to the performance requirements seen in Table 2-1. The values provided in this section represent expected subsystem mass and power based on experience and heritage hardware.

Spacecraft Mechanical Subsystem: The requirement for the s/c structure is that it be able to interface with the launch vehicle and TM and accommodate the s/c subsystems. The primary s/c structure is a large cylindrical shell that surrounds the SXT, plus additional structures that envelop the optics. S/c equipment is mounted to this structure. The s/c needs no major structural deployment mechanisms. A central monocoque cylinder with radial stiffener provides the structural load path between the modules and the launch vehicle interface.

Separation of the s/c from the launch vehicle occurs by means of a non-pyrotechnic, low shock, lightweight, one-fault-tolerant system. The mechanical interface from the s/c to the launch vehicle consists of two half circles that join to the bottom platform of each s/c. These remain attached to each s/c upon separation while the lower common truss adapter ring remains attached to the launch vehicle.

Thermal Subsystem: The Thermal Subsystem easily meets the requirements, as highly stable conditions exist in the L2 environment. This orbit allows the use of inexpensive and reliable passive thermal control technologies as used on many other NASA s/c. The s/c exterior is covered with MLI blankets, and thermal radiator panels maintain s/c components within a safe temperature range. Thermostatically controlled heater circuits are also provided for components of the hydrazine propulsion system, batteries, etc. A low-conductivity mounting system joins the TM and the s/c and limits heat exchange between them.

Attitude and Orbit Control Subsystem (AOCS): The primary requirement of the AOCS is to point

Table 2-3: Observatory Attitude Performance Specifications

Description	Parameter	Specification	Note
Pointing Range	Roll	± 20 degrees	Max
	Pitch	± 20 degrees	Max
	Yaw	± 180 degrees	
Star Tracker Attitude Knowledge 3σ Accuracy	Roll	60 arcsec	
	Pitch	3 arcsec	
	Yaw	3 arcsec	
Telescope Pointing Determination (Aspect) 3σ Accuracy	Pitch	5 arcsec	Ground-based post processed
	Yaw	5 arcsec	
Pointing Control 3σ Accuracy	Roll	60 arcsec	
	Pitch	30 arcsec	
	Yaw	30 arcsec	
Pointing Stability	Pitch	0.6 arcsec/sec	Max
	Yaw	0.6 arcsec/sec	Max
Pointing Jitter	Roll	5 arcsec	Max
	Pitch	2 arcsec	Max
	Yaw	2 arcsec	Max

and stabilize the SXT boresight to the intended X-ray source and maneuver efficiently between targets (see Table 2-3). In addition, the AOCS nulls tipoff rates and performs all other maneuvers after separation from the launch vehicle, including momentum management and orbit adjustments. Constellation-X does not scan except for rastering during boresighting.

The AOCS uses proven component designs: digital controllers hosted on the on-board computer (OBC); an analog safehold controller contained within the attitude control electronics (ACE); eight coarse Sun sensors placed to provide coverage and redundancy at all attitudes and to process attitude information during initial acquisition, maneuvers, and safe modes; a star tracker for mission attitude sensing and which enables the observatory to have sufficient accuracy, knowledge, and stability for its attitude; an inertial reference unit (IRU) that computes the angular rates of the observatory to provide dynamic attitude information to the Command and Data Handling (C&DH) computer; four reaction wheels (RWs); a propulsion subsystem; and associated interface electronics. The sensors interface with the ACE, which also interfaces with the C&DH computer. This computer processes AOCS sensor data and commands the RWs or thrusters to control the attitude of the satellite. Each Constellation-X observatory will nominally be held in a 3-axis stabilized, inertial attitude using a star tracker as the primary reference and a 3-axis rate integrating gyro package for determination of attitude rates. It will be able to report its orientation (referenced to the star tracker) to within 3 arcsec, 3σ. (See Foldout 2 for a diagram of the AOCS.)

In this system, gyro bias and drift-induced errors are removed by frequent updates from the star tracker. Requirements on the gyro package are therefore derived requirements, based on top-level attitude requirements, and will be determined during the design phase. Gyro "jitter," or high frequency-angle noise, will also affect attitude stability and accuracy; specifications will be derived in the design phase. There are several standard, space-qualified gyro packages available that can meet project requirements.

No mechanisms will be operated nor antennas moved during science observations, so no science data will be compromised. The solar arrays are fixed.

Periodic on-orbit instrument calibrations for several different items including telescope boresights, best focus, effective area, resolution, and contamination are planned. All of these calibrations will use standard science observations and will place no added requirements on the AOCS. The system is sized to accomplish maneuvers between targets in less than one hour.

All data will be telemetered to the ground for further processing. Ground-based processing, using forward and backward Kalman smoothing plus calibration, will produce more accurate attitude estimates for the aspect solution.

Command and Data Handling Subsystem : The C&DH Subsystem is configured to manage the command and data requirements from the instruments and s/c as indicated in Table 2-4. It processes the commands received from the ground and data from the observatory subsystems and the instruments. It also manages the timekeeping functions. The C&DH subsystem can be seen in Foldout 2.

Communications Subsystem: Communications Subsystem requirements are to support telemetry, commanding, ranging, and science data transmission to the ground stations. Each

Table 2-4: C&DH Subsystem Requirements

Description	Requirement	
Mission level science data ingest rate • Average mission science data rate • Mission bright source data rate	 192 kbps 2.56 Mbps	
Observatory data ingest rate (per observatory) • Science • Instrument housekeeping • Spacecraft housekeeping Total	Daily Average (kbps) 48 4 4 56	Peak (kbps) 640 4 4 648
Observatory X-band downlink rate	1.7 Mbps	
Observatory S-band downlink data rate	2 kbps	
Observatory S-band uplink data rate	2 kbps and 150 bps	
Spacecraft time distribution accuracy	± 10 microseconds	
Spacecraft time synchronized to UTC accuracy	± 10 microseconds	
Time resolution	± 10 microseconds with ± 1 microsecond goal	
Observatory data storage	42 Gbits minimum based on contact time of 300 minutes every 4 days	

observatory carries its own communications subsystem consisting of a primary S-band coherent uplink/downlink for commanding/ranging and a low-rate downlink for housekeeping telemetry. An 8250-MHz X-band downlink transmits science and s/c engineering data.

S-band uplink frequency is 2096 MHz. The 2-kbps uplink commands are phase-modulated on a 16-kHz subcarrier. The S-band downlink is a 2-kbps phase-modulated signal at 2250 MHz. The S-band antenna system consists of two omnidirectional antennas, each providing a hemispherical gain pattern. An S-band hybrid combines the antenna signals. The S-band transponder provides transceiver functions and coherent turnaround ranging. The transponder transmitter output of 5 W is increased to 26 W by an external power amplifier (PA). The output of the PA is passed through a band reject filter and diplexer combination to protect the transponder receiver input circuitry. The X-band equipment consists of a 5-W X-band BiPhase Shift Keying (BPSK) transmitter followed by a 1.2-m 37-dB high gain gimbaled antenna system.

Link analysis has been performed by the GSFC Communications Link Analysis and Simulation System (CLASS). The worst-case link margins are: S-band uplink 6.3 dB, S-band downlink 3.8 dB, and X-band downlink 3.9 dB.

Electrical and Power Subsystem (EPS): The EPS supports the orbital average load through all mission phases, as stated in Table 2-7. The EPS provides conversion, generation, storage, control, and distribution of unregulated power for the operation of all s/c subsystems and components. It performs power balance, battery charge control, power distribution, power safing, and ground power interfacing functions.

The subsystem consists of a solar array, battery, and power supply electronics (PSE). The solar array is a 6.2-m square, 28% efficient, body-mounted panel that provides 1525 W beginning of life (BOL) and 1442 W end of life (EOL) power to support the required load plus losses. One 40AH eight-cell battery provides energy storage. The orbit is a full Sun orbit with no eclipses. Battery power will be required from the launch phase until Sun acquisition occurs. It will also be used during peak load periods at a limited duty cycle and during safing events. The PSE is a direct energy transfer (DET) system that converts solar energy to electrical energy and provides it directly to all s/c loads at an unregulated voltage from 22-32 V. The EPS is simplified by the operational constraint that observing will only be within 28 degrees of the plane that is perpendicular to the Sun-Earth line.

The EPS design incorporates functional redundancy. The solar array is composed of multiple strings, and the system can tolerate the loss of several strings without affecting mission science. The PSE uses a staged power control configuration that can tolerate the loss of a single stage. Battery-charging circuitry enables safe charging. Software allows the EPS to be re-configurable to compensate for system degradations. The battery consists of at least eight cells and incorporates bypass switches that allow it to bypass a bad cell without affecting mission performance. Multiple switched and unswitched output services are provided with cross strapping of critical functions.

The electrical subsystem will provide adequate grounding and shielding to prevent noise from affecting the operation of each subsystem and instrument. To accomplish this, classical methods of equipment bonding, ground isolation, and a single point ground design will be coupled with minimum path signal ground returns to minimize induction, noise, and ground bounce.

Propulsion Subsystem: The Propulsion Subsystem is required to provide launch vehicle tip-off management, lunar phasing and swingby, orbit insertion and corrections at L2, and momentum unloading. The consumables requirement for a six-year mission amounts to a 177 m/s ΔV. The subsystem is a blowdown monopropellant hydrazine system. A total of 180 kg of propellant is loaded to provide the 177 m/s ΔV. The BOL pressure is 2757.6 kPa (400 psi) and the EOL pressure is 689.4 kPa (100 psi). Each set of four redundant thrusters can perform all the functions required by the propulsion subsystem. Preliminary assessment indicates no plume impingement concerns; however, further analysis is planned. The components are listed in Table 2-5.

Flight Software (FSW): Functional requirements of Constellation-X flight software include FSW Executive services (e.g., central processing unit (CPU) modes, commands, telemetry, time management, external hardware bus management); C&DH applications such as stored command handling, telemetry event detection, and response; radiation effects detection and handling; onboard data storage and playback from the on-board data memory; ground communications and antenna gimbal management; active power management and battery control (very similar to the power control accomplished on the MAP mission); L2 orbit acquisition and maintenance (reference data modeling and thruster controls); sensor data processing; actuation command generation and output; maneuvers and science target inertial fine pointing (attitude determination and control); momentum management; safing control modes; s/c to science instrument interface and instrument-unique support; and autonomous anomaly/failure detection and responses.

FSW for each observatory will be identical except for s/c ID, calibration factors, flight hardware-unique parameters, and unique parameters required for ground interface. FSW will be exhaustively tested on the highest fidelity FSW test bed. Changes in FSW will be exercised via only a regression test set. FSW staff will support each observatory's I&T activities as well as launch preparations and transition to normal operations. Constellation-X FSW will benefit from the knowledge gained from the MAP mission with Lissajous orbit at L2.

Table 2-5: Propulsion Components Specifications

Propulsion Component	Size	Qty
Hydrazine tank	55 cm OD sphere	3
22.24 N thruster	7 cm OD, 18 cm length	8
Miniature fill and drain valve	7 cm length, 1.4 cm OD max.	6
Filter	8.4 cm length, 1.5 cm OD max.	1
Pressure transducer	6 cm length, 5 cm OD	3
Isolation valve	5 cm x 7 cm x 8 cm	3
Miscellaneous hardware	0.635 cm OD tubing, etc.	N/A

2.4.1.3 Resources

Tables 2-6 and 2-7 indicate estimated mass and power resources for the instruments and the s/c subsystems. The estimated resources do not include any contingency. However, the sum of contingency and margin for the entire observatory is sufficient for implementation. During mission formulation, the instruments and subsystems will be allocated contingency out of the margin, depending on the maturity of design, production, and testing.

Mass Budget: The total mass estimate for each observatory and launch vehicle is shown in Table 2-6.

Power Budget: The power estimate for each observatory is shown in Table 2-7.

2.4.2 Ground Segment Architecture

The Constellation-X ground data system consists of four principal data processing elements:

Table 2-6: Observatory Mass Estimate

Item	Total Mass (kg)
Telescope Module	
SXT FMA (w/o RGA)	642
RGA	50
RFC	33
HXT mirrors and detectors (3)	151
XMS	147
Thermal	29
Integration and miscellaneous materials	81
Structure and mechanisms	454
Subtotal for TM	**1587**
Spacecraft Bus	
Structure and mechanisms	342
Power	67
Thermal	18
Propulsion hardware	35
AOCS	68
C&DH and control electronics	18
Communications	85
Integration materials	76
Propellant	180
Subtotal for s/c	**889**
Total per observatory (wet)	**2476**
Total wet launch load (two observatories)	4952
Total dry launch load (two observatories)	4592
Launch vehicle performance	6498

$$\%\text{MassMargin} = \frac{\text{LaunchVehiclePerformance} - \text{LaunchLoad}}{\text{DryLaunchLoad}} \times 100 = 34\%$$

Table 2-7: Observatory Power Estimate

Item	Average Power (watts)	Peak Power (watts)
Telescope Module		
Thermal		
SXT mirrors and RGA	300	310
HXT mirrors	36	40
OM	35	40
OB	50	55
FPM heaters	25	30
Thermal subtotal	**446**	**475**
Electronics		
TM mech. controller	2	5
RFC	40	45
XMS electronics/ADR	80	146
Cyrocooler	150	200
HXT electronics	30	35
Radiation detector	10	10
Electronics subtotal	**312**	**441**
Spacecraft Bus		
Communications	10	60
C&DH	45	45
AOCS	160	240
Propulsion	41	90
EPS	36	36
Thermal	25	25
Subtotal for s/c	**317**	**456**
Total per observatory	**1075**	**1412**
Solar array EOL	1442	

$$\%\text{PowerMargin} = \frac{\text{SolarArrayEOL} - \text{ObservatoryAvg.Load}}{\text{ObservatoryAvg.Load}} \times 100 = 34\%$$

the Tracking, Telemetry and Command (TT&C) facility, the Flight Dynamics Facility (FDF), the MDS, and the Science Data System (SDS). The MDS and SDS are co-located at the CXSOC. The FDF is at GSFC. The Constellation-X ground segment requirements are developed in the initial Constellation-X Operations Concept document; key requirements that drive the ground system are shown in Table 2-1. The Chandra ground system architecture is based on a multiple mission support design and can be extended at low cost to support Constellation-X.

CXSOC Science and Mission Operations: The CXSOC science and mission operations consists of the facilities, data systems, and staff required to conduct the mission operations and all aspects of the science program including s/c and science instrument operations, calibration, mission planning, data system development, mission and science data archiving, distribution and analysis, public education and outreach, and grants programs. These activities are conducted from a single facility in order to reduce operations costs and maximize team integration and synergy.

Spacecraft and Instrument Health and Safety: Constellation-X will use an integrated health/safety processing system combined with a telemetry data capture and science processing facility to minimize operational staffing requirements.

Tracking, Telemetry and Command Facility: The TT&C facility is baselined to consist of two commercially provided ground stations (required to achieve the orbit determination accuracy commensurate with the 100-microsecond timing requirement [Table 2-1]), with network connectivity to the CXSOC. Each station consists of an 11-m antenna plus RF and digital hardware and commercial off-the-shelf (COTS) software necessary to provide and interface with S- and X-band space/ground links. Facility remote control capability over a network is required. COTS station scheduling aids will be executed by the MDS using predicted orbits as required. Each station shall have the capability to generate sufficient status data (“monitor data”) so that station configuration and health can be assessed remotely at any time (i.e., regardless of whether a contact is ongoing or not). The ground stations are responsible for on-board data memory capture via the X-band downlink. Commands, real-time and dump telemetry, tracking, and monitor data are recorded at the station and retained for at least one week. A maximum requirement of 25 Gbytes results from the worst-case assumption of network outages. Operational margins will be imposed for manual re-dumps in the event of TOOs or downlink anomalies in addition to design margin. Command and telemetry data will be formatted using Consultative Committee for Space Data System (CCSDS) recommendations. Different virtual channels will be used for real-time, playback, and other data streams.

Flight Dynamics Facility: The FDF provides trajectory design, OD for early mission, maneuver planning, and calibration for ΔV burns and for orbit analyses as needed for the duration of the mission.

Mission Data System: The MDS performs the traditional mission data processing functions for the s/c platforms including commanding, real-time safety and health monitoring, trending, anomaly resolution, and for science instrument health and safety. The MDS consists of the data system resources required for commanding the s/c, real-time health and safety monitoring of s/c and science instrument engineering data, observatory and science instrument scheduling, scheduling tracking support, power management, thermal management, orbit and attitude verification, and on-board computer file management. The MDS provides the capabilities for Constellation-X operations planning and observatory and contact scheduling, as well as command interface to the TT&C facility and real-time data displays to the FOT during communications contacts. All commands and data sent to the observatories are under strict configuration management and are archived in the Mission Archive. The MDS is capable of generating and validating uploads within 24 hours in response to TOO requests. The MDS receives s/c and science instrument housekeeping data from the TT&C ground station, removes the artifacts of the space-to-ground transmission, and provides quality annotation as part of the data validation process. It also provides the capability to limit check and monitor exceptions to both real-time and back-orbit on-board data memory.

Science Data System: The SDS provides for all science processing functions including data validation, pipeline processing, management, and distribution of calibration and science data within the required 2-week period to the GO, and support for dissemination of images and data to the public. The SDS supports planning of science observations and science operations decisions such as the observation of calibration targets or TOOs, archives the scientific data products into the Mission Archive, distributes validated data and software to the user community, and supports the GOs. The SDS generates standard products, including calibration products, on subsets of Constellation-X data (using algorithms and/or software specified or provided by the CXSOC science staff) and generates products that require information from multiple instruments, as well as information from other observatories. The SDS provides capabilities for observation evaluation and planning, as well as science instrument monitoring, configuration, and software maintenance. It also provides software that can be used to interactively analyze the data returned from the science instruments, assisting in data validation and instrument health monitoring. This software is portable within UNIX operating system (OS) variants and can be provided to observers for use on their computer facilities. This software shall use the same core processing code as the automated processing pipelines that produce the standard products and shall utilize adopted scientific standards for data formats and exchange (e.g., FITS, TCP/IP). The SDS can process 12 hours of data in approximately two hours, is easily capable of meeting the 2-week data delivery requirement; the limiting step is the downlink intervals and receipt of data from the TT&C facility.

Using the SDS, the science processing team performs pipeline processing on the instrument and ancillary data to remove instrument artifacts and register the events on the sky, producing standard Event Lists and other Level 1 products. Level 1 products are processed further to produce images, spectra, and time series Level 2 products. The time to process the data depends on the type of observation and the SDS implementation but is expected to be one hour per 12-hour period of data.

The design of both the MDS and SDS will use COTS hardware exclusively and COTS software to the extent possible. Both data systems will use a common architecture and application interfaces, and will include automation of routine operational functions wherever possible. The intent is to reserve operational personnel resources for non-routine activities. This architecture minimizes costs by centrally receiving and managing all mission data including longterm storage, accountability, and distribution. This architecture also minimizes costs by centralizing and consolidating systems requiring high reliability and availability.

2.4.3 Data Validation, Analysis, and Archiving

Validation: The CXSOC is responsible for verifying the scientific results, detecting anomalies in the hardware and the software, reporting and documenting errors, and diagnosing and correcting problems. As in the Chandra experience, a combination of automated and manual checks (by scientists) will verify integrity of science data and identify any problems with the software and its products. These checks will allow both predictable and unpredictable problems to be detected while minimizing the labor required. Validation applies to instrument performance, data processing algorithms, and scientific analysis algorithms, and to meta-data.

Implementation Phase—A testing procedure will be designed in parallel with the software coding and verification effort to allow automated and reproducible testing of the scientific performance of all aspects of the software and its products. Test procedures will be prepared corresponding to the test requirements. Tests will be designed in terms of each scientifically distinct analysis task. Each step will generate sufficient output to provide traceability of spurious results. The testing procedure will be a natural extension of the software testing and verification activity performed and will be applied to all software subsystems in each software release.

A test dataset will be developed from actual Chandra, XMM-Newton, and Astro-E2 data, as well as simulated Constellation-X data, to be used for cross-mission validation. It will include examples of each type of data Constellation-X will collect, with sufficient variety to fully exercise the software, and will contain representative examples of all known source properties. The example source detection will require data containing extended sources, many weak point sources, strong point sources, and combinations of these. Both the testing procedure and dataset will be developed in parallel with the software and will be designed so that all or part of the software can be tested at a given time. The datasets used in testing and verification will be used/modified whenever possible to minimize duplication of effort.

An automated checking procedure will be developed to check the output products of both the standard processing and the testing procedure for: existence of relevant data files, presence in output files of standard keywords, results of analyses that are outside pre-defined ranges compared with the known input data (e.g., negative fluxes). The procedure will generate a report of checks made and their results and will enter them into a database.

Mission Operations Phase

➟*Calibration Objects:* Pre-mission testing and checking procedures will be modified to run on a set of specific cosmic sources to be used as calibration objects; results will be stored in a calibration database. Analysis of the calibration database will continue to ensure that software and products are scientifically correct.

The set of celestial calibration sources will include objects with a variety of spatial, spectral, and flux variability properties. These sources will be located throughout the sky and by definition will address the calibration requirements of each instrument. For each calibration source, an allowed range for each derived quantity will be specified and the automated checking procedure will flag any values outside these ranges.

➟*Scientific Observations:* During the mission, data quality is thoroughly monitored so that the mission's scientific productivity will be maximized. A combination of manual checks by the CXSOC scientists and automated verification procedures will enable this to be achieved effectively.

The automated checking procedure will be applied to the output products of all observations. CXSOC scientists will review the automated checking output and will manually inspect all outputs of the archives. Any anomalies will immediately be evaluated in detail, with analysis continuing until the problem is understood and appropriate corrective actions taken. The results of all stages of this process will be reported and archived, so that problems and the resulting corrective measures are documented. Once approved, the processed data, along with the output of the checking procedure and the scientist's report will be archived in the products database with appropriate protection. All are considered part of the standard data products generated by the CXSOC for the observer. The scientist's check will be made on a confidential basis. Should unexpected scientific results be apparent, the scientist will do no more than alert the observer.

➟*Level 3 Validation:* Standard Level 3 catalog products also require evaluation to assure they are scientifically correct. For example, catalogs including positions of stellar objects must be compared with positions of their optical counterparts to ensure the absence of systematic positional errors. Catalogs of X-ray line identifications must likewise be validated. Spectral parameters must be checked against those derived from high-resolution studies and against X-ray sources observed by previous missions.

Data Analysis: The CXSOC science staff, in coordination with the instrument teams, will define the suite of science tools for the standard processing and analysis environment. For cost effectiveness, these tools are extensions of those used by Chandra (the CIAO system). The CIAO release includes the GUI analysis applications PRISM and TOOLAGENT, the SHERPA modeling and fitting application, the ChIPS plotting and imaging application, three source detection tools, several instrument specific tools, and numerous data manipulation tools (e.g., dmcopy, dmlist, dmextract). This package includes tools to create, extract, calibrate, and analyze data from Event Lists and to produce and analyze images, spectra, and time series from these Event Lists. In addition to the tools and applications, a number of software libraries (e.g., the Data Model, ChIPS) are present within src/lib and src/libdev of the source code distribution and can be used to build new tools and applications. All source code will be freely available in support of any CIAO release. The Science Data Systems Division, with the active participation of science staff, will develop, distribute, and maintain these tools. The science staff will make these tools available to observers and the scientific community through the public portion of the Constellation-X web site.

Data Archiving: Based on the expected nominal daily average data rate for all three instruments (estimated from the ODRM and extrapolated from Chandra observations of comparable sources) plus engineering data, the Constellation-X mission will generate a total of ~1 Tbyte of raw data per year. Including Level 1 products and higher-level products, as well as reprocessed data, yields an estimated total data archive requirement of approximately 10 Tbytes per year, corresponding to 40 Tbytes for the four-year mission lifetime required and 100 Tbytes if the mission reaches its lifetime goal. The raw data must be validated, processed, and ingested into the archive within 24 hours of receipt from the TT&C facility.

All raw telemetry data are archived, as are processed engineering and science data, ancillary data, and higher-level products. The SDS saves all event data in FITS format in the Constellation-X Data Archive. The Constellation-X Data Archive will be updated both when new data are accumulated and when the data are reprocessed as the understanding of the instruments improves on orbit. Archived Level 1 and Level 2 data products will be available to the observer over the Internet. Observation data will have a nominal proprietary period during which the data will be available only to the relevant observer(s). Following expiration of the proprietary period, the data will be accessible by the wider community through the public portion of the Constellation-X Data Archive. Calibration observations are always public. The CXSOC staff is responsible for protecting the archived data from inadvertent loss or unauthorized disclosure, but may access proprietary data only if required for Constellation-X operations. Mirror sites will replicate the public portion of the Constellation-X Data Archive for wider geographical access. Upon mission termination, all data will be delivered to the High Energy Astrophysics Science Archive Research Center (HEASARC).

2.5 Approach to Mission Success

The success of Constellation-X is being assured through the adoption of proven mission assurance practices during development and implementation. These include implementing a comprehensive quality program consistent with ISO 9001; following accepted systems engineering practices; conducting appropriate and timely trade studies; using flight-proven and mature designs wherever possible; adopting suitable redundancy and reliability concepts; parts and materials selection following I&T procedures appropriate for multi-satellite missions; adhering to GSFC procedures for environmental testing; and strictly adhering to contamination control measures and exposures.

2.5.1 Heritage and Maturity of Mission Elements

Spacecraft Bus: Constellation-X is fortunate in that, although the science it will conduct is breaking new ground, it is able to take advantage of mature technologies and elements. Most Constellation-X s/c components are being patterned after flight-qualified components used on MAP, Swift, EO-1, or other NASA missions. A few will require slight modifications that can be accommodated easily. A high percentage of s/c components will be flight proven (Table 2-8).

Ground Segment—The CXC at SAO has supported the Chandra mission and will be supporting Constellation-X operations in the next phase. The FDF supports all missions launched by GSFC.

Launch Vehicle—NASA and the U.S. Air Force are developing launch vehicles that can be used for Constellation-X. The successful maiden flights of Atlas V and Delta IV occurred in 2002. The payloads carried on these flights were actual commercial payloads, not dummy loads, thus demonstrating the users' confidence in these rockets' reliability. By the time Constellation-X is ready for launch, it is expected that a minimum of 44 Atlas Vs and 20 Delta IVs will have been launched.

Table 2-8: Flight Heritage of Constellation-X Components

Component (Typical)	Past Vendors (Examples)	Flown On (Examples/ Similar)
Mechanisms/covers	SAI, BASD	FUSE, STIS, MSO/GRO
Spacecraft structures	GSFC, SAO	MAP, Chandra
TM structures	COI, Ball, TRW, Kodak	Chandra
Star trackers	Goodrich	P-81, GLAS
Wheels/drivers	ITHACO	TRMM, RXTE
Inertial reference units	Litton	NEAR, TDRSS, EO-1
NiH_2 battery	Eagle Pitcher	HST, MAP, GOES, AQUA, Terra
Solar array	EMCORE	RHESSI, ICESat, Starshine3
Hydrazine tanks	PSI	STEP, ROCSAT
Thrusters (22 N)	Atlantic, Primex	MAP, TRMM
Processors	BAE Systems	Swift, Triana
Ultra stable oscillator	FEI, JHU/APL	RXTE, TRMM, GRACE

2.5.2 Redundancy and Reliability Measures

Redundancy: Constellation-X shall be configured so that no single failure will result in the loss of more than 25% of mission science, excluding launch vehicle failure. A constellation of four observatories may meet this requirement by means of selective redundancy; however, full redundancy is the goal. Failure Mode, Effects and Criticality Analysis; Fault Tree Analysis; and Probabilistic Risk Analysis will be performed to identify critical components needing redundancy. These risk reduction activities will ensure mission success in a cost-effective way. It is expected that the C&DH processor, RWs, etc., will be redundant.

Reliability: A high degree of reliability means that there is a high probability that the mission will achieve its science objectives. The reliability criterion is that the probability of success that 75% of mission science will be available over the mission design life is 0.75. This reliability is achieved by careful selection of parts, processes, and redundant elements in design. The design will be carefully analyzed for parts stress, worst-case analysis, and reliability prediction. Thus, reliability is carefully designed into the system and will follow MIL-STD guidelines.

The components, assemblies, and observatories will go through burn in, environmental testing, stress tests, and comprehensive performance tests at all levels. At the conclusion of the test program, the flight segment shall have demonstrated minimum reliability acceptability by trouble-free performance testing for at least the last 300 hours of testing. Major hardware changes during or after the test program will invalidate the previous demonstration. All the above measures will weed out the infant mortality and ensure high reliability.

2.5.3 Integration and Test

Instruments are delivered flight-qualified for I&T. Each detector and its electronics will be integrated onto the FPM in parallel with integration of the FMA and HXT mirrors into the OM. Both will be functionally and environmentally tested and aligned.

The FPM and OM will be integrated onto the OB to become the TM. The TM will undergo alignment and integrated functional testing.

The TM will be integrated with the s/c to become the observatory. The s/c will arrive integrated and environmentally tested. Integration will consist of mechanical and electrical integration, mating of the TM to the bus, functional testing, and comprehensive performance testing (CPT), where the observatory performance baseline will be established. Mission operations activities will also be performed. This is an important risk reduction strategy and has proven useful on Chandra and SIRTF in uncovering system-level problems. Mission operations activities include use of operational databases and procedures and “day-in-the-life” and mission scenario tests.

Observatory environmental testing (ET) will be performed. A protoflight ET program will be performed on the first set of hardware, while an acceptance ET program will be performed on the remaining three identical sets of hardware, thereby reducing cost and schedule. Functional tests will be performed before and after each environmental test. Post-environmental activities will be performed, which will include alignment, functional, and CPT to reverify the baseline. A schematic of the I&T test flow is shown in Figure 2-1.

Multiple teams will be used for parallel processing of the four observatories, per the schedule shown in Appendix B.

GSE is to include instrument-provided detector stimulators and simulators, mirror stimulators, thermal GSE and s/c provided high-fidelity s/c simulators.

Plans for each segment of testing will be used to control the I&T process. These will include, but are not limited to, an Observatory Verification Plan; an Assembly, Test, Launch, and Operations Plan; a Contamination Plan; Instrument Verification Plan(s), etc. A complete list of plans that will be used to govern the I&T process will be part of a Constellation-X Documentation Tree.

2.5.4 Contamination Control

Each component of the Constellation-X observatory will be evaluated for molecular and particulate contamination sensitivities and requirements. The components sensitive to contamination are the SXT mirrors and gratings, HXT mirrors and detectors, the CCD array, cooler, calorimeter, sunshade, and s/c thermal control surfaces, star trackers, antennae, and solar panels. Allowable contamination levels at EOL are 100A for SXT and HXT optics and detectors and 200A for the solar panels and sunshade.

The project will develop a Contamination Requirements document and a Contamination Control Plan to monitor contamination buildup throughout mission lifetime. Further, detailed contamination control plans will be developed for each instrument and for the integrated s/c. Body-mounted witness mirrors will be periodically analyzed to assist in the monitoring activity.

2.5.5 Product Assurance Activities

Constellation-X will use the traditional GSFC approach to Product Assurance, reaping the benefit of an independent look from personnel with years of experience in the Office of Systems Safety and Mission Assurance (OSSMA) Directorate. A System Assurance Manager (SAM) will be assigned to the Project, and will be responsible for implementing the Product Assurance program. The OSSMA is an organization independent from

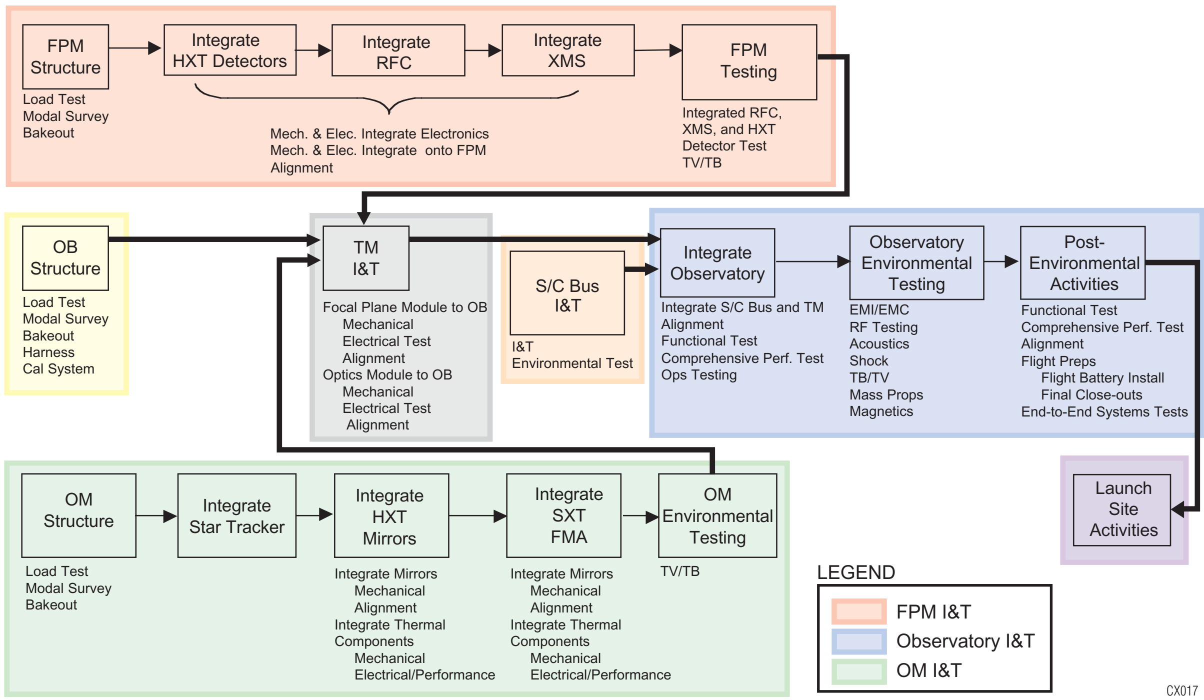


Figure 2-1: I&T Test Flow

the Flight Programs and Projects Directorate (FPPD), which ensures an independent path for verification of assurance requirements. The activities include safety, hardware and software quality; software independent verification and validation (IV&V) (performed at the West Virginia facility); reliability, parts, and materials, processes; workmanship; independent system reviews, and nonconformance/corrective action processes. Specific workforce levels are included in the Project budget to cover each of these areas.

Independent reviews will be performed in the GSFC Integrated Independent Review Team (IIRT) approach, as described in GPG 8700.4D, "Integrated Independent Reviews." The independent reviews currently planned for Constellation-X are the Technology Readiness and Implementation Plan (TRIP), Systems Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), Pre-Environmental Review (PER), Pre-Shipment Review (PSR), Operations Readiness Review (ORR), Missions Operation Review (MOR), Flight Readiness Review (FRR), Launch Readiness Review (LRR) and Peer Reviews. This list includes all the major reviews required for GSFC-managed missions.

During the formulation phase, a Mission Assurance Requirements (MAR) document will be developed by the SAM. This will specify the requirements that all elements have to follow. The SAM will then monitor each element during design and build to ensure compliance with the MAR. The requirements will also be called out in each contract, and flowed down to subcontractors. Parts and materials must meet requirements driven by the reliability and contamination requirements (discussed in Section 2.5.4). The reliability approach is discussed in Section 2.5.2.

2.5.6 Systems Engineering

Plan and Philosophy: The systems engineering approach for Constellation-X follows the guidelines detailed in GPG 7120.5, "Systems Engineering" (draft). The collaborative approach uses expertise from GSFC and SAO. It is led by GSFC management, draws its lead systems engineers (SEs) from each organization, using their combined experience of more than 40 years in s/c missions, including X-ray missions such as Chandra. As the mission progresses into the implementation phase, a systems engineering IPT will be formed, consisting of SEs from all elements of the project–each instrument, s/c, telescope, project

SEs (including mission systems, s/c systems, and instrument systems), and mission operations—and led by the Mission Systems Engineer. Regular meetings of the IPT will ensure communication across all systems.

The overriding responsibility of the SE staff is to ensure that all systems work together and that issues that cut across different systems are identified, resolved, verified, and tracked. To achieve this, key systems engineering activities have included initial mission architecture design, which used discipline engineering support at GSFC and SAO and inputs from industry. Other key systems engineering activities include interface control, requirements flowdown, control and verification, assigning and managing technical resource allocations (e.g., mass and power), and design optimization including trade studies. Analyzing mission environments and obtaining independent insight at milestone reviews (e.g., SRR, PDR, CDR, etc.), as well as peer reviews, will be done.

Constellation-X has identified the key mission science requirements, which are delineated in the draft "Top-Level Requirements" document. These have been flowed down to component-level requirements in the "Requirements Flowdown" document. SEs will track, trace, and monitor the requirements during the implementation phase using a database tool such as DOORS. The validation and verification of each requirement will also be done by systems engineering. When Constellation-X requirements are baselined (during the formulation phase), they will be put under project configuration control and can be changed only with approval of the Constellation-X Configuration Control Board (CCB), which includes the SEs and is chaired by the Project Manager. Managing technical resources for each element also falls in this category–changes are monitored by the SEs and recommended to the CCB.

As specified in GPG 7120.5, the two Constellation-X documents written to date, included as reference documents, are the Reference Mission Description document and the Operations Concept document. A Systems Engineering Management Plan will be developed during the project formulation phase.

Constellation-X will use a prime contractor for the combined s/c and TM. This is a distinct advantage because it enhances the contractor's ability to perform end-to-end systems engineering for the observatory. The contractor's SEs will be part of the Project-led IPT, tying them in with the rest of the mission systems.

Trade Studies: Optimization of the mission reference architecture is an ongoing process and includes trades that have been identified to reduce cost, as well as to increase performance. Design optimization includes monitoring the interfaces between elements, which necessitates systems engineering cognizance of Interface Control Documents (ICDs). Risk management is also an important aspect of systems engineering and is described in Sections 4.1.1.7 and 4.1.2.7. To refine and enhance the reference mission concept and architecture, and develop cost effective high-quality requirements, further studies will be conducted during the formulation phase of the mission. The trades already completed have effectively used the Constellation-X teaming and management structure, inspiring confidence in the completion of future trades. The primary trades already conducted are listed in Table 2-9, as well as future trade studies that have been identified.

2.5.7 Equipment and Facilities

Constellation-X has modest requirements for equipment and facilities. Ground-support equipment (GSE) for the detectors will include instrument-provided detector stimulators and simulators, mirror stimulators, thermal GSE, lifting and handling GSE, alignment GSE, and s/c simulators. GSE for the TM will also include TM-provided lifting and handling GSE. GSE for observatory I&T will include s/c-provided lifting and handling GSE, ground system (GS), umbilical, power, and RF GSE.

Integration facilities will include a cleanroom of sufficient size and cleanliness for TM and observatory I&T, a crane for lifting operations, and a control room to house the GS, umbilical, power, and RF GSE, and the I&T team.

Environmental facilities will include EMI/EMC, vibration, acoustics, TV/TB, mass properties, and magnetics test chambers. The X-Ray Calibration Facility (XRCF) at MSFC will be used for X-ray testing and calibration of the FMA wedge assembly.

Table 2-9: Mission Trade Studies

Trade	Options	Drivers	Status/Selection
Number of observatories in constellation	12, 8, 6, 4, 3, 2, 1	Cost, schedule, science requirements reliability	4 baselined; 2 will be studied further in Phase A
Number of SXT FMAs	12, 8, 6, 4, 3, 2, 1	Effective area, s/c accommodation, ground test, cost	Closed/4 selected
Orbit	HEO/L2/LEO	Thermal environment Viewing efficiency	Done/L2
Launch vehicle	Delta II, Atlas III, Delta IV, Atlas V	Cost, performance	Done/Atlas V baseline, Delta IV backup option
Cryo system	Stored cryogen or mechanical system	Mass and life	Done/mechanical system
Timing	USO, crystal oscillator	Long-term accuracy	Done/USO
Grating design	• In-plane • Off-plane	Effective area, resolution	Ongoing/end FY03
Ground station	• Dedicated • Commercial	Cost Timing capability	Commercial at present; redo before launch
SXT contamination requirements	Level of cleanliness	Effective area, image quality, calibration accuracy	Future/SRR
Need for on-board radiation monitor	• EPHIN-like detector • Commercial detector (CEASE) • None	Protection of instruments from radiation damage	Future/SRR
Need for focal plane electron suppression	• None • Magnetic broom	Detector background	Future
Fiducial light system	• None • Chandra-type system • Lower cost alternate	Angular resolution (15 arcsec), OB stability	Done/none For angular resolution of 5 arcsec, may be revisited
Focus mechanisms	• One for both CCD and calorimeter • Separate mechanisms for CCD and calorimeter • None	Image quality, risk reduction	Future/PDR
On-board calibration sources	• Radioactive source(s) • Electron impact source	Need to maintain calibration throughout mission life	Future/PDR
Optical bench construction	• Truss with stray light closeout • Shell	Mass, stray light protection	Future/PDR
SXT calibration	• Full aperture testing in 1 G • Sub-aperture testing	Calibration accuracy	Future/CDR
HXT optics	• Segmented glass • Full shell Ni	• Multilayer deposition • Mass	Mid FY04